STUDIES ON AIR INGRESS FOR PEBBLE BED REACTORS

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ABSTRACT

A loss-of-coolant accident (LOCA) has been considered a critical event for helium-cooled pebbled bed reactors. Following helium depressurization, it is anticipated that unless countermeasures are taken air will enter the core through the break and then by molecular diffusion and ultimately by natural convection leading to oxidation of the in-core graphite structure and graphite pebbles. Thus, without any mitigating features a LOCA will lead to an air ingress event. The INEEL is studying such an event with two well-respected light water reactor transient response codes: RELAP5/ATHENA and MELCOR.

To study the degree of graphite oxidation occurring due to an air ingress event, a MELCOR model of a reference pebble bed design was constructed. A modified version of MELCOR developed at INEEL, which includes graphite oxidation capabilities, and molecular diffusion of air into helium was used for these calculations. Results show that the lower reflector graphite consumes all of the oxygen before reaching the core. The results also show a long time delay between the time that the depressurization phase of the accident is over and the time that natural circulation air through the core occurs.

1. Introduction

New and safer nuclear reactors (Generation IV reactors) are now in the early planning stages in many countries through out the world. One of the reactor concepts being seriously considered is the Pebble Bed Modular Reactor (PBMR) of which several preliminary reference designs have been developed [1,2]. To achieve public acceptability, these reactor concepts must show an increased level of inherent safety over current reactor designs, i.e., a system must be designed to eliminate any concerns of large radiological releases outside the site boundary. As such, the analysis of severe accidents such as an air ingress using well-validated computer codes such as MELCOR, RELAP5/ATHENA or other thermal-hydraulic codes specifically developed to analysis PBMR must be performed.

As a result of this new interest in Generation IV reactors the NRC held in October 2001, a two-and-a-half day workshop [3] on high temperature gas reactor safety and research issues, where a number of high priority issues were identified. Several issues that were identified include the development of thermal-hydraulic and safety analysis codes, the need for an adequate database to validate the codes and accident phenomenology for air ingress events and the resulting consequences.

Over the past three years the Idaho National Engineering and Environmental Laboratory (INEEL), through the use of Laboratory-Directed Research and Development (LDRD) funds, has collaborated with the Massachusetts Institute of Technology (MIT) to explore the use of the PBMR as a viable alternative to present reactor designs. As a small part of the overall funding we at the INEEL are investigating the use of proven thermal-hydraulic reactor accident codes sure as MELCOR (with some modifications) to analyze the air ingress accident. The main advantage of using such codes (provided it can be shown that they are qualified for such analyses) is that they are available now and many of their thermal-hydraulic models have been validated against test data over the past twenty years. Thus, the needed validation and verification effort to qualify these codes for PBMR safety analyses and licensing activities should be greatly reduced.

This paper will address the air ingress accident associated with a reference PBMR design being developed by MIT and INEEL. We will show that the results generated using the safety analysis code MELCOR are consistent with experimental results reported in the literature [4]. RELAP/ATHENA results will be published later.

2. Accident and model description

The air ingress accident is considered to be an accident that poses a serious threat to the integrity of the fuel and subsequent the release fission products to the site boundary. For an air ingress accident to occur, we are postulating that the primary coolant inlet and outlet ducts experience a simultaneous complete double guillotine break between the reactor vessel and the high-pressure turbine, which is located in an adjacent auxiliary equipment room. This room will be referred to as the vault in this paper. Following rupture of the primary ducts, depressurization of the reactor will occur. The depressurization event last only a few seconds until the pressure in the reactor core comes to equilibrium with the pressure of the vault. Based on Japanese experimental data [4] and results in this paper, it is expected that little or no air will flow into the reactor core for many hours after the initiation of the accident.

A preliminary MELCOR model of a reference PBMR was developed to model a LOCA and subsequent air ingress event. MELCOR [5] is a severe accident code being developed at Sandia National Laboratory for the U. S. Nuclear Regulatory Commission to model the progression of severe accidents in light water nuclear power plants. However, due to the general and flexible nature of the code other reactor concepts such as the pebble bed reactor can be modeled. In this paper we are using a modified version of MELCOR 1.8.2. These INEEL modifications to MELCOR 1.8.2 were the implementation of multi-fluid capabilities [6] and the ability to model graphite oxidation. The multi-fluid capability allows MELCOR to use other fluids such as helium as the primary coolant.

A schematic of the reactor configuration under consideration is shown in Figure 1. The reactor was assumed to have a core diameter of 3.5 m and a active core height of 8.0 m yielding a total core volume of 76.9 m^2. The core of the reactor was divided into three radial zones and eight axial zones for a total of 24 core control volumes. The core control volumes are cylindrical and are centered about the core centerline. The inner radial zone contains 69,700 non-heated pebbles. The two outer radial zones contain a total of 342,900 heat-generating pebbles producing a total of 270 MW of thermal energy.

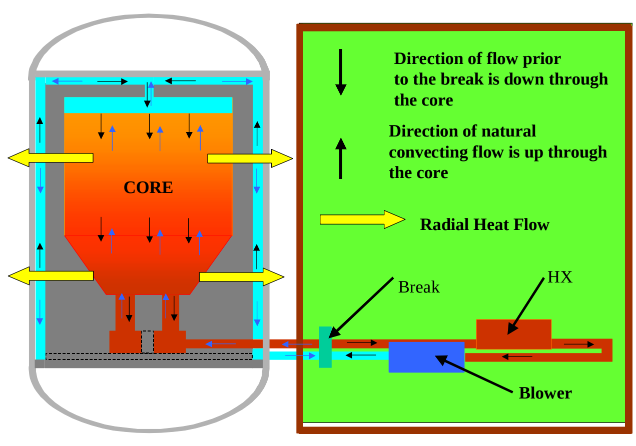

Fig. 1 Schematic of pebble bed reactor and vault

For nominal operating conditions the coolant enters the bottom of the reactor at 450 ^{o}C, flows up an annular flow channel located between the reactor side reflector and the reactor vessel. The coolant then flows radially along the top of the reactor exiting into a plenum above the core. From the plenum the coolant flows down through the core and exits the bottom of the core at 850 ^{o}C. The coolant then flows to the power conversion unit, which is represented simplistically by several control volumes. The double-ended rupture of both the inlet and outlet pipes as shown in Figure 1 is represented in the model as two valves that are connected to the vault and are opened at the beginning of the decompression accident. For this calculation the vault volume was estimated to be 27000 m^3 and is assumed to be isolated from any outside air. When details of the vault geometry are available the vault volume will be updated.

The heat transfer from the pebbles is dominated by convection during nominal operation of the reactor. However, during the LOCA when the flow in the core decreases to near zero the heat generated by the pebbles is removed by conduction and radiation through the pebbles to the graphite reflector. The heat is then conducted through the reflector, radiated to the reactor vessel wall, conducted through the vessel wall, and then removed from the outside of the vessel by natural convection and radiation. The pebbles in the core were modeled as spherical heat structures, one heat structure per control volume. Radial conduction from each zone of the core was modeled as a homogenous cylindrical conduction. This conduction was then applied to the spherical heat structure by dividing the conduction terms by the number of pebbles in the zone. We have validated our modeling approach by matching our model against cylindrical transient heat conduction solutions. The heat transfer from the one structure was then multiplied by the number of pebbles in the control volume to obtain the overall heat transfer from all the pebbles in the volume.

Since this is a preliminary calculation, the heat transfer from the outer surface of the graphite reflector to the outside heat sink was modeled as radiation heat transfer through two radiation shield representing the reactor vessel wall and the vault wall. In other words the thermal conductance of the two walls were neglected, as was the natural convection from the reactor vessel to the environment abjection to the vessel. Axial conduction in the core and in the lower graphite reflector was also modeled. The air ingress event is assumed to occur after the reactor has been operating for many hours at steady state conditions.

2.1 Oxidation Model

As stated above, the main objective of this study was to evaluate the capability to model the oxidation of the reactor graphite structure (reflector and core) due to an air ingress accident. The graphite oxidation kinetics shown in Figure 2 was implemented in MELCOR. The present model is based on graphite oxidation rates obtained experimentally at the INEEL by O'Brien et al., as reported in Reference [7].

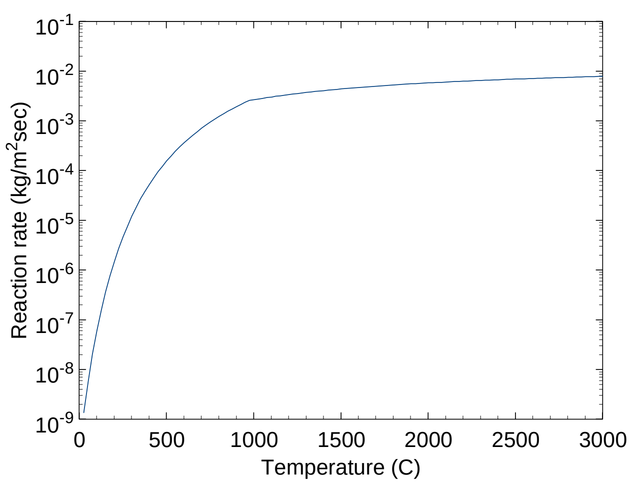

Fig. 2 Graphite oxidation rate as a function of graphite surface temperature

The rate equation is based on the oxygen concentration in air at standard atmospheric conditions. Thus, in the MELCOR model as a first order approximation, the oxidation rates are assumed to vary linearly with the oxygen partial pressure. It is also assumed that only CO_2 is produced during the oxidation process. The heat generated from the exothermic reaction is deposited directly into the surface node of the graphite layer being oxidized.

3. Results

The LOCA was initiated by opening the two valves that connect the hot and cold legs to the vault. The blower was tripped and the reactor was scrammed at the beginning of the accident. The simultaneous double-ended rupture of the hot and cold legs causes a rapid depressurization of the primary coolant system. The pressure in the reactor equalizes with the vault pressure at 0.15 MPa in ≈ 1.5 seconds.

The mass flow rate of air through the core is shown in Figure 3. After the depressurization phase of the LOCA, the mass flow rate of air through the core due to natural convection is essentially zero until approximately 214 hrs. At this time, the flow suddenly increases from zero to 0.080 kg/sec indicating the onset of natural circulation through the core. The flow rate through the core remains between 0.080 kg/sec and 0.075 kg/sec from 214 to 400 hours, the time when the transient was terminated.

After the depressurization stage, hot helium occupies the core, the upper plenum, and the inlet annulus regions of the reactor with cool heavy air at the entrance of the pipe breaks. In this configuration there is insufficient buoyancy force to support natural convective flow. Thus, little or no mass flow of air from the containment to the core and from the core to the containment occurs for a number of hours. During this phase of the accident, air from the containment is mainly transported to the reactor by molecular diffusion. This delay in the onset of natural convection is supported by Japanese and German experimental high-temperature gas-cooled reactors air ingress results [4, 8].

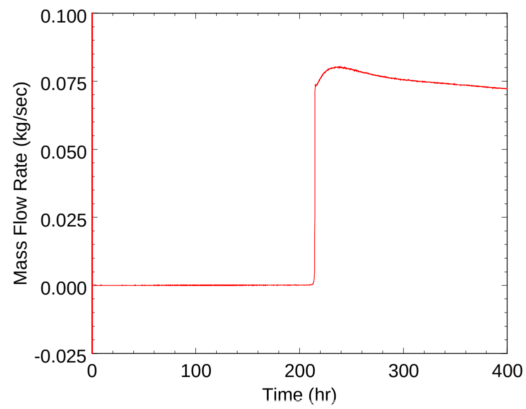

Fig. 3 Mass flow rate through the core

The mole fraction of air (nitrogen) in the core and upper plenum of the reactor calculated by MELCOR gradually increases (shown in Figure 4) until the buoyancy force is large enough to initiate natural circulation. As depicted in the figure, the mole fraction of nitrogen in the core gradually increases from zero at the beginning of the accident to ≈ 0.45 by means of molecular diffusion and what little natural convection that exists just before the onset of natural convection. When natural convection starts, the mole fraction of oxygen immediately starts to decrease with a corresponding increase of carbon dioxide in the vault. This indicates that oxidation of the graphite in the reactor is occurring.

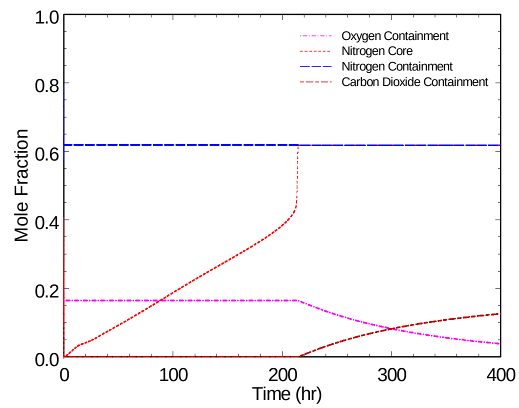

Fig. 4 Mole fraction of gas components in the reactor and containment

When natural circulation of the air from the containment begins the temperature of the lower reflector graphite located below the core immediately experiences a sharp rise in surface temperature as shown in Figure 5. This rise in temperature is the result of surface oxidation of the graphite. As shown in the figure the temperature of the lower graphite surface starts to increase, going from less than 500 ^{o}C to a maximum of 890 ^{o}C in 34 hours. At 248 hours the lower reflector graphite starts to cool off because the concentration of oxygen in the feed stream has been depleted to the point where the heat removal by the convective flow and radial conduction is greater than the energy generated by oxidation. The lower upper portion of the reflector graphite just below the core experiences very little oxidation because the graphite below this region depletes all the oxygen. The first layer of pebbles in the core experiences little or no oxidation during the ≈ 200 hours when oxygen is flowing to the bottom of the reactor. In fact the results indicate that the first layer of pebbles immediately starts to cool off due to the natural convection flow.

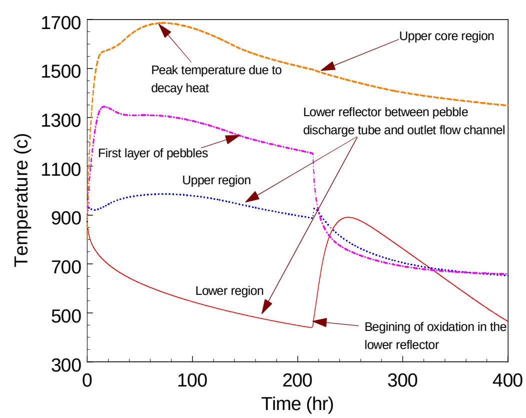

Fig. 5 Temperature history of core and lower reflector region

The maximum temperature that the pebbles in the core experience during the transient is 1685 ^oC. As show in the figure, this peak temperature occurs early in the transient and is due to decay heat. This peak temperature is greater than the allowable fuel particle temperature of 1600 ^oC but with a more detailed model and better exterior boundary conditions the maximum core temperature is expected to fall below the maximum allowable fuel particle temperature.

4. Conclusions

The preliminary results presented in this paper indicate that oxidation of the PBMR pebbles will probably not be a major concern for release of large amounts of fission products in any air ingress event. The oxidation of lower reflector graphite appears to consume all the available oxygen before it can reach any of the fuel in the core. This is a result of the mass flow rate due to natural circulation being very small. Sensitivity calculations are planed where the availability of oxygen in the vault will be varied and different oxidation rates will be used.

The onset of natural convection appears to take days to occur. Thus, if required countermeasures can be taken to mitigate the consequences of an air ingress accident. The prediction of the timing of the onset of natural circulation depends on how well the code used is able to predict the molecular diffusion of the air through the helium in the core. This phenomenon is strongly dependent on the flow characteristics through the core (e.g. friction losses) and subsequent thermal response. Therefore we plan to benchmark MELCOR against the Japanese experimental results presented in Reference 6. With the benchmarking complete, we will then take what we have learned and apply it to our PBMR model. It appears that present day safety analysis codes such as MELCOR can with a few modifications be used to analyze reactor accidents associated with the PBMR.

5. References

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6. Acknowledgment

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